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Acquisition of 3D Subsurface Well Data and 3D GIS for the Ventura Basin, California

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Abstract

In the Ventura basin, faults and folds accommodate high rates of oblique crustal strain and uplift rates exceed 10 mm/yr. To improve our understanding of how faults and folds develop in oblique convergence, and to test the reliability of 2D models to predict 3D subsurface structure, we acquired a unique 3D dataset for the Ventura Basin provided by the Ventura Basin Study Group (VBSG). The VBSG study consists of 17 structure contour maps and 84 interlocking cross section data panels based on nearly 1200 correlated deep-penetration wells. The wells vary in depth from 1 to 5 km. Many of these wells drill active fault and fold structures associated with major fault systems, including the San Cayetano, Oak Ridge, and Santa Susana faults. This integrated 3D study is based on wire-line logs, mud logs, paleontological reports, core analyses, and surface maps. Each data panel typically ties in 4 directions to define the sides of a 3D data volume or cell. The result is a 3D presentation of an enormous quantity of high-quality subsurface data that have been reconciled into a coherent geological interpretation. Any 2D or 3D kinematic model of the basin and its associated fault and fold geometry, as well as any valid estimate of the seismic hazard, must incorporate these data if it is to be successful. The VBSG structure contour maps and cross sections are now available to the entire NEHRP research community from our website at **http://www.crustal.ucsb.edu/hopps**.

Introduction

The western Transverse Ranges are one of the most active tectonic regions of the world. Active convergence and rapid subsidence across the Ventura Basin has produced uplift rates that exceed 10 mm/yr and one of the thickest sections of Plio-Pleistocene strata ever found [*Yeats et al.,* 1994]. Geologic and geodetic data indicate that the Ventura Basin currently accommodates high rates of oblique crustal strain [*Donnellan et al.,* 1993; *Huftile and Yeats,* 1995] including components of regional tectonic rotation. Significant amounts of oblique convergence (up to 7 mm/yr) have also been documented across the eastern Santa Barbara Channel [*Larsen et al.,* 1993]. The 1994 M6.7 Northridge earthquake occurred on a blind, south-dipping fault beneath the San Fernando Valley that is considered part of the active fault and fold system that extends westward into the Ventura Basin and eastern Santa Barbara Channel [*Yeats and Huftile,* 1995] (**Figure 1,** top). This fault system is currently active at the microearthquake level [*Ziony and Jones,* 1989; *O'Connell,* 1995].

Other major active faults have been identified for the greater Los Angeles metropolitan region [*e.g., Dolan et al.,* 1995]; yet little is understood about these active tectonic structures, or about the hazard associated with these blind faults, because little has been done to document the nature or subsurface geometry of these structures in 3D. This is because acquiring, correlating, and interpreting sufficient subsurface data to accurately resolve such 3D structure is typically a very expensive and time-consuming task. In many areas, the only available data were collected for hydrocarbon exploration and much of these data are still inaccessible.

Understanding this complex system of active faults and folds is inherently a three-dimensional problem, yet many of the recent approaches used to infer deep

subsurface structure have involved mainly 2D balanced cross section models [*e.g., Suppe and Medwedeff,* **1990;** *Namson and Davis,* **1991;** *Shaw and Suppe,* **1994**]—models that are now being widely applied throughout much central and southern California (**Figure 2**). These 2D models make precise, testable predictions on the location and orientation of deep fault structure; the dip and depth of active faults and detachments; the geometry of fault-related folds; and the rate of fault slip. These 2D models failed, however, to predict the presence or geometry of the south-dipping fault revealed by the 1994 M6.7 Northridge earthquake (**Figure 3**).

Because of the significant hazard such earthquakes pose, and the extensive use of such 2D models to provide seismic hazard estimates in California [*Dolan et al.,* **1995**], it is imperative that independent tests are made of the validity of these 2D models, and—to some extent—how these initial, retrodeformable 2D models will need to be modified to incorporate 3D components of crustal deformation. To date, many of the results using balanced cross section techniques are simply model driven, and only reflect the dip-slip component of crustal deformation. Many characteristics exhibited by these 2D models have yet to be independently verified by direct observation. The net result is widely varying interpretations for the same active geologic structure [e.g., *Suppe and Medwedeff,* **1990;** *Shaw and Suppe,* **1994;** *Kamerling and Nicholson,* **1995,** *Huftile and Yeats,* **1995;** *Stone,* **1996**].

To address these issues, we have begun to develop an integrated, geologic/geophysical database of active 3D fault and fold structure for the Ventura Basin. This database will include industry drillhole data, surface geologic maps, subsurface seismic reflection images, correlation cross sections, subsurface structure contour maps, topography, gravity, seismic velocity studies, and detailed analysis of the local seismicity. The idea is to use this database to evaluate the geometry and displacement of faults, the evolution of fault-related folds, basin development, the pattern of subsurface strain in space and time, and the reliability of simple 2D models to infer deep seismogenic fault structure.

The primary area of focus for this study is the Ventura Basin and eastern Santa Barbara Channel (**Figure 1,** top). This region is an area of active oblique convergence that has been extensively investigated by industry for the purposes of hydrocarbon exploration and production. Within the onshore portion of the Ventura Basin alone, there are an estimated 14,000 drill-holes. Over a 5-year period, the *Ventura Basin Study Group* (VBSG) [*Hopps et al.,* **1992**] conducted a systematic study of the structure and stratigraphy within the basin and of its associated fault and fold structures. This study consists of a detailed, integrated analysis of nearly 1200 deep-penetration (1–5 km) correlated wells. Many of these wells used in the study drill active fault and fold structures associated with major fault systems, including the San Cayetano, Oak Ridge, Red Mountain and Santa Susana faults (**Figure 1,** bottom).

The VBSG produced a set of 17 subsurface structure contour maps for various formation (time) horizons (**Figure 4,** top) that tie together in a grid of 21 structure cross sections consisting of 84 interlocking cross section data panels. An example of part of one such data panel is shown in **Figure 4** (bottom). All the data panels are of similar quality and exhibit similar subsurface well control. Each panel typically ties in 4 directions to define the sides of a 3D data volume or cell. Section panels jog

from well to well so that data are not distorted by projection into the line of the section. The result is a 3D presentation of an enormous quantity of high-quality subsurface data that have been assembled and reconciled into a coherent geological interpretation.

There are thus several important scientific issues that this study will help address, not the least of which is improving our understanding of the seismic hazards for the Santa Barbara-Ventura area. Almost all of our seismic hazard studies are based on our ability to infer deep subsurface structure and processes from surface or near-surface observations. The VBSG study and dataset provide a detailed description of 3D subsurface structure—as it has been actually drilled—to depths of several kilometers over a large region that includes a complicated pattern of active subsurface faults and growing folds. Any 2D or 3D kinematic model of the basin and its associated fault and fold structures, or any estimate of the regional seismic hazard must incorporate the VBSG subsurface data, if it is to be successful. Any model that fails to adequately satisfy these data, is unlikely to correctly predict deeper structure at seismogenic depths.

The complete integrated 3D dataset of subsurface information, that includes the VBSG well data, maps and cross sections, as well as seismicity, seismic reflection, topography and geodetic results, can be used to:

1) Define the 3D geometry of active subsurface faults and related folds in oblique convergence and to describe how these fault and fold structures vary along strike;

2) Test the reliability of 2D balanced cross section models for western Transverse Ranges structure;

3) Define 3D basin geometry to improve 3D wave propagation and basin response models;

4) Provide a better understanding of the structures at depth accommodating measured geodetic strain, including how thrust and strike-slip faults may interact;

5) Define the evolution of displacement fields in space and time by 3D map restoration (unfolding) of different structure (time) horizons and by cross section analyses;

6) Provide an internally consistent 3D volume of subsurface data to test the reliability of various techniques and model studies to accurately infer deep subsurface structure from near-surface data.

Purpose of Project

There are two primary purposes of this project:

1) To acquire the Ventura Basin Study Group (VBSG) database of subsurface well information files consisting of nearly 1200 correlated deep-penetration wells, as well as the results of the VBSG study that includes 17 structure maps and 84 structure cross section data panels that were produced using these subsurface data.

2) Establish an on-line digital subsurface database of the Ventura basin, starting with the VBSG study and dataset. This evolving 3D database, which will eventually include maps, cross sections, well files, seismic reflection data and seismicity, will

provide: (a) the framework for developing improved 3D models of how faults and folds develop in oblique convergence; (b) the ability to test and evaluate the reliability of 2D models to predict 3D subsurface structure; and (c) improve our understanding of the seismic hazards associated with these major fault and fold systems that comprise one of the most active tectonic areas in southern California.

Results

Funding for this project began April 17, 1997. No FY98 funds were received. This progress report thus covers the nominal 12-month period extending from about mid-April 1997 to mid-April 1998. Most of the available FY97 funds were expended in the first 6 months of the contract period.

The VBSG proprietary study and dataset were successfully acquired and are now available through a unique data license negotiated by ICS on behalf of NEHRP and the Southern California Earthquake Center (SCEC). The VBSG maps and cross sections have been scanned and are currently available as jpeg images from our ICS website. **Figure 5** (top) shows a screen image of the VBSG website in operation. The website includes a clickable cross section index map (**Figure 6**) that allows users to individually view selected cross section images, as well as a clickable thumbnail catalog of all the VBSG structure contour maps and cross sections. A preliminary Java map applet of the evolving 3D GIS database is also available, along with a VRML demonstration of the potential 3D capability of the dataset (**Figure 5,** bottom).

Preliminary analysis shows that the VBSG dataset provides significant subsurface information regarding the location, orientation, and geometry of active subsurface fault strands—several of which had not been previously identified. For example, this study, which was completed in 1992, clearly identifies active blind south-dipping faults in the footwall of the Santa Susana fault (**Figure 7,** top), well before the 1994 Northridge earthquake, which occurred on just such a south-dipping blind fault. Other features clearly evident in the VBSG dataset include non-planar faults (**Figure 7,** bottom), basin subsidence, evidence of earlier normal faulting, significant variation in pre-folding depositional thicknesses and material strengths of rocks, high-angle reverse-separation fault geometry, and significant changes in fold orientation with time and space. These observations are consistent with the reactivation of earlier normal-separation faults in transpression—causing in some places basin inversion—and the accommodation of regional strain through rotation and significant components of strike-slip or oblique-slip motion. These observations, based on actual subsurface structure as it has been drilled, are not consistent with previously published 2D balanced cross section models that presume moderate to low-angle fault dips, planar fault surfaces, homogeneous layers of uniform thickness, the absence of strike-slip or oblique-slip motion, and the absence of any pre-existing structure that would control initial fault and/or fold geometry.

We have also begun initial analysis of the VBSG structure map and cross section interpretations using various kinematic and compatibility constraints, and have begun the incorporation of other independent data into the Ventura basin dataset. The VBSG study and dataset only includes information from wells and surface geologic maps. It does not incorporate seismic reflection, gravity, or earthquake

data, which provide important independent information on the geometry of major subsurface reflectors, the depth to basement, and the location, orientation, and sense of slip of active seismogenic faults. For example, **Figure 8** shows recent seismicity recorded by the SCSN, as well as results from our study of the 1996 Ojai earthquake sequence [*Nicholson and Kamerling,* 1998]. The recent better-located hypocenters define a north-dipping structure whose surface outcrop would coincide with the Red Mountain fault (RMF) and two south-dipping 'back-thrusts' that would coincide with the Arroyo Parida and Santa Ynez faults. The 1996 Ojai mainshock occurred at a depth of 18 km and exhibited an oblique-reverse focal mechanism with a low-angle north-dipping fault plane and a relatively high-angle south-dipping plane consistent with either slip on the Red Mountain thrust or a possibly a steep south-dipping oblique fault. The 1996 aftershocks, however, delineate a curviplanar structure that defines a previously unsuspected fault whose extrapolated surface trace would also coincide with the approximate location of the Santa Ynez fault (**Figure 8,** top).

This particular pattern of active subsurface faults—as defined by seismicity—has not been included in any previously published 2D model studies for the region. It also represents a significant departure from the standard planar low-angle thrust geometry often assumed for faults in many 2D balanced cross sectional models. More importantly, these results indicate that active oblique-slip faults, like the Santa Ynez fault, often have steeper dips and extend to greater crustal depths (14- 18 km) than inferred from the 2D models (**Figure 2**)[*Namson and Davis,* 1992]. This pattern of seismicity—and the rapid basin subsidence—is also inconsistent with the presence of a presumed flat detachment beneath the central Ventura Basin (**Figure 2**) [*Huftile and Yeats,* 1995]. Thus, combining the VBSG dataset with other subsurface information (such as seismicity) can be particularly effective in developing an improved understanding of how fault and fold structures in the near-surface connect with—and are related to—faults at seismogenic depths.

Besides providing important geologic and geophysical constraints on the location and geometry of active subsurface faults, this combined, integrated Ventura basin dataset can provide important, critical information on the distribution of finite strain with time, including fault slip rates. The basis for this procedure is the quantification of the cumulative deformation sustained by different stratigraphic (time) horizons using various kinematic and compatibility requirements. **Figure 9** (top) shows a 3D perspective of the eastern portion of a structure contour map of one such time horizon (~1 Ma) originally identified and mapped by *Yeats* [1981]. Using the VBSG data, high-resolution seismic reflection profiles, and available subsurface well data, we modified, improved, and extended this map, especially in the offshore area where the original mapping was incomplete [*Kamerling et al.,* 1998]. Once digitized, this revised structure contour map becomes a quantitative, digital estimate of the cumulative deformation sustained by the time horizon since the stratigraphic layer was produced ~1 Ma.

By using 3D map restoration techniques originally developed by *Gratier et al.* [1991], we can recover the finite strain field represented by this deformed surface. The technique assumes certain kinematic and compatibility constraints, the primary

one being that the deformation sustained is conformable. **Figure 9** (bottom) shows the results of our preliminary analysis [*Kamerling et al.,* 1998]. Each block shows the %strain accommodated within each block as a result of folding. Additional displacement vectors are recover between blocks as a result of fault motion and block rotation. These results indicate that the Oak Ridge fault accommodates both reverse and strike-slip motion, and that both components of slip (offset) extend well out into the Santa Barbara Channel. This model result also suggests that the amount of strike-slip is fairly uniform along east-west segments (~1.7 km), and may be less than half the 3.4 km of left-slip previously inferred by *Yeats and Taylor* [1990]. Careful analysis of the data shows that there are several other stratigraphic horizons that can be used to document such finite strain fields at other time periods, thus providing a quantified, sequential image of the finite deformation with time. Such information is crucial to our understanding of how fault, fold and basin geometry evolves, as well as how measured geodetic strain may be currently partitioned between potentially seismic and aseismic processes.

In addition, these preliminary kinematic and compatibility analyses have already identified several places were the VBSG interpretations can be improved, including the identification of two previously unsuspected faults that may act to segment the greater north-dipping Red Mountain–San Cayetano–Santa Susana fault system. Moreover, since fault geometry must be compatible with the kinematic properties of the slip they accommodate, the 3D geometry of fault surfaces can be inverted using fault intersection points and fault slip directions. And lastly, combining the VBSG dataset with seismicity has proved particularly effective in developing improved understanding of how active fault and fold structures in the shallow and near-surface crust connect with—and are related to—deeper faults at seismogenic depths.

Future Work

Assuming that continued funding for this project becomes available, we hope to:

- Provide internet access to the VBSG database of well information files. This requires converting current well descriptions into useful GIS coordinates.
- Link the VBSG 3D dataset of maps, cross sections, and well information files to an on-line mapping application, and to other GIS relational databases.
- Continue to evaluate and improve VBSG subsurface interpretations of maps and cross sections using various kinematic and compatibility constraints.
- Integrate the VBSG dataset with other subsurface information, such as seismicity, gravity, and available seismic reflection data.
- Tie the observed onshore 3D subsurface structure and geology in the Ventura basin to equivalent features observed offshore in the Santa Barbara Channel.
- Construct isopach maps of various formation intervals to help identify possible piercing points, lines or planes, and thus evaluate the magnitude of both the horizontal and vertical cumulative fault motion.
- Evaluate finite displacement fields using 3D map restoration techniques.
- Provide improved estimates of the seismic hazard based on this integrated 3D database of subsurface fault, fold, and basin geometry and related slip rates.

Data Availability

The entire VBSG study of 17 maps and 84 cross sections is now available from our website at **http://www.crustal.ucsb.edu/hopps**. This website has already proven useful to a number of people working in southern California. In its first 4 months of operation (September 1997 to January 1998), it sustained 12,000 hits from 500 external (i.e., non-UCSB) users, indicated a high-frequency of repeat customers. Preliminary results of our on-going 3D map restoration project and analysis of finite strain fields are available at **http://www.crustal.ucsb.edu/vbmrp**. Specific information regarding the VBSG study and dataset is available by contacting Craig Nicholson or Marc Kamerling at ICS.

Reports Published

Nicholson, C., D. Valentine, M.J. Kamerling, and T.E. Hopps (1997), 3D subsurface structure of the Ventura Basin: Analysis of active fault and fold development in oblique convergence, *SCEC 1997 Annual Meeting Report,* Costa Mesa, p.78-79.

Nicholson, C., D. Valentine, M.J. Kamerling, and T.E. Hopps (1997), 3D subsurface structure of the Ventura Basin: Analysis of active fault and fold development in oblique convergence, *Eos (Trans. AGU)*, **v. 78,** n. 46, p. F632.

Nicholson, C., D. Valentine, M.J. Kamerling, and T.E. Hopps (1998), 3D subsurface data of the Ventura Basin: Testing the reliability of 2D models to infer deep fault structure in the western Transverse Ranges, *Seismol. Res. Lett.,* **v. 69,** p. 161.

Nicholson, C. and M.J. Kamerling (1998), Reliability of 2D kinematic fold models to infer deep fault structure in the western Transverse Ranges, California, *Proceedings of the NEHRP Conference and Workshop on the Northridge, California Earthquake,* **v. II,** p. 299–306.

Kamerling, M.J., C.C. Sorlien, and C. Nicholson (1998), Subsurface faulting and folding onshore and offshore of Ventura basin: 3D map restoration across the Oak Ridge fault, *SCEC 1998 Annual Meeting Report,* Palm Springs, p.68-69.

Bibliography

Bullard, T.F. and W.R. Lettis, 1993, Quaternary fold deformation associated with blind thrust faulting, Los Angeles basin, California, *J. Geophys. Res.,* **98,** p. 8349–8369.

Davis, T.L., J. Namson and R.F. Yerkes, 1989, A cross section of the Los Angeles area: Seismically active fold and thrust belt, the 1987 Whittier Narrows earthquake, and earthquake hazard, *J. Geophys. Res.,* **94,** p. 9644–9664.

Dolan, J.F. and K.E. Sieh, 1992, Tectonic geomorphology of the northern Los Angeles basin: Seismic hazards and kinematics of young fault movement, 35th AAPG Field Trip Guidebook, p, B20-B26.

Dolan, J.F., K.E. Sieh, et al., Prospects for larger or more frequent earthquakes in the Los Angeles metropolitan region, *Science,* **v. 267,** p. 199–205, 1995.

Donnellan, A., B.H. Hager, R.W. King, and T.A. Herring, Geodetic measurement of deformation in the Ventura Basin region, southern California, *J. Geophys. Res.,*

v. 98, p. 21,727–21,739, 1993.

Donnellan, A., B.H. Hager, R.W. King, and T.A. Herring, Discrepancy between geological and geodetic deformation rates in the Ventura basin, *Nature,* **v. 366,** p. 333–336, 1993.

Gratier, J.P, et al. (1993). Partition between seismic and aseismic deformation in California, SCEC report, reprinted in *U.S. Geol. Surv. Open-file Report 94-228,* p. 279–300.

Gratier, J.P., B. Guillier, A. Delorme and F. Odonne, Restoration and balance of a folded and faulted surface by best-fitting finite elements: principles and application, *J. Struct. Geol.,***13,** 111-115, 1991.

Gratier, J.-P. and B. Guillier, Compatipility constraints on folded and faulted strata and calculation of total displacement using computational restoration (UNFOLD program), *J. Structural. Geol.,* J.G. Ramsey Special Issue, v. 15, p. 391–402, 1993.

Gratier, J.P. (1995). Displacement field and geometric compatibility using computational restoration of folded and faulted strata: application to the last 3–4 Ma in the Ventura and Los Angeles basin, *EOS (Trans. AGU),* **v.76,** p. F143.

Gratier, J.P., T. Hopps, T. Wright, and C. Sorlien (1997). Recent crustal deformation in southern California deduced from the restoration of folded and faulted strata, preprint, 20 pp.

Hauksson, E. and L.M. Jones, The 1987 Whittier Narrows earthquake sequence in Los Angeles, southern California: seismological and tectonic analysis, *J. Geophys. Res.,* **94,** p. 9569–9590, 1989.

Hester, R.J. and J.N. Truex (1977). San Cayetano fault field trip, AAPG Pacific Section, 35 pp.

Hopps, T.E., H.E. Stark, and R.J. Hindle, Subsurface data in basin analysis: An example from Ventura Basin, California, *SCEC Workshop: Thrust Ramps and Detachment Faults in the Western Transverse Ranges,* UC Santa Barbara, p. 10, January, 1995a.

Hopps, T.E., H.E. Stark, and R.J. Hindle, Subsurface geology of Ventura Basin, California, *Ventura Basin Study Group Report,* 45 pp., 17 structure contour maps and 84 structure panels comprising 21 cross sections, Rancho Energy Consultants, Inc., Santa Paula, CA, 1992.

Hopps, T.E., H.E. Stark, R.J. Hindle, J.H. Thompson, and G.C. Brown, CS30: Correlated section across Central Ventura Basin from T5N/R19W to T1N/R18W, California, *Pacific Section–Am. Assoc. Petrol. Geol. Cross Section,* April, 1995b.

Huftile, G.J., H. Tsutsumi, C.L. Schneider and R.S. Yeats, Geologic evidence for thick-skinned deformation in the Western Transverse Ranges, California, *SCEC Workshop on Thrust Ramps and Detachment Faults in the Western Transverse Ranges,* p. 12, UC Santa Barbara, January, 1995.

Huftile, G. and R.S. Yeats, Convergence rates across a displacement transfer zone in the western Transverse Ranges, Ventura basin, California, *J. Geophys. Res.,* **v. 100,** p. 2043–2068 (1995).

Hummon, C., C.L. Schneider, R.S. Yeats, J.F. Dolan, K.E. Sieh, G.J. Huftile, Wilshire fault: Earthquakes in Hollywood?, *Geology,* **22,** p.291–294 (1994).

Kamerling, M.J. and C. Nicholson, The Oak Ridge fault in the central Santa Barbara Channel, *Eos (Trans. AGU),* **75,** p.622 (1994).

Kamerling, M.J. and C. Nicholson, Reliability of 2D kinematic models to infer deep structure in the western Transverse Ranges, California, *Eos (Trans. AGU),* **v. 76,** n.46, p. F349 (1995).

Kamerling, M., Sorlien, C. C., and Mayerson, D., Post-Miocene strike-slip along the southern Hosgri fault system, California, determined from map restoration: *EOS-Trans. AGU* (1996).

Keller, E.A, L.D. Gurrula, J.G. Metcalf, and T.W. Dibblee, Jr., Earthquake Hazard of the Santa Barbara Fold Belt, California, *SCEC Workshop Field-Trip Guidebook,* UC Santa Barbara, January, 1995.

Lees, J.M., Xmap8: A free computer program for three-dimensional GIS, *Seismol. Res. Lett.,* **v. 66,** p. 33–37 (1995).

Namsom, J., 1987, Structural transect through the Ventura basin and western Transverse Ranges, in *Structural Evolution of the Western Transverse Ranges,* Pacific Section, S.E.P.M., **48A,** p. 29–41.

Namson, J. and T.L. Davis, 1988, A structural transect of the western Transverse Ranges, California: Implications for lithospheric kinematics and seismic risk evaluation, *Geology,* **v. 16,** p. 675–679.

Namson, J. and T.L. Davis, Detection and seismic potential of blind trusts in the Los Angeles, Ventura, and Santa Barbara areas, and adjoining Transverse Ranges, *USGS Final Technical Report,* **1991.**

Nicholson, C., L. Seeber, P. Williams and L.R. Sykes. Seismicity and fault kinematics through the eastern Transverse Ranges, California: Block rotations, strike-slip faulting and low-angle thrusts, *Journal of Geophysical Research,* **91,** 4891-4908, (1986a).

Nicholson, C. and J.M. Lees, Xmap8 — Interactive Color Graphics for Analysis of GIS and 3D Geophysical Data: Demonstration and Program Capabilities, *Eos - Trans. AGU,* **v.75,** p. 456 (1994).

Nicholson, C., C.C. Sorlien and B.P. Luyendyk, Deep crustal structure and tectonics in the offshore Southern Santa Maria Basin, California, *Geology,* **20,** p. 239–242 plus plate (1992).

Nicholson, C., C.C. Sorlien, and M.R. Legg, Crustal imaging and extreme Miocene extension of the inner California Continental Borderland, *Geol. Soc. Amer. Abstr w/Progs,* **25,** 418 (1993).

O'Connell, D., Earthquake locations, focal mechanisms, and GPS near Ventura, Western Transverse Ranges, California: The crust has a thick skin, *Eos (Trans. AGU),* **76,** n.46, p. F141 (1995).

Olsen, K.B., R.J. Archuleta, and J.R. Matarese, Three-dimensional simulation of a magnitude 7.75 earthquake on the San Andreas fault, Science, v. 270, p. 1628-1632, 1995.

Olsen, K.B., and R.J. Archuleta, 3D simulation of earthquakes on the Los Angeles fault system, Bull. Seismol. Soc. Am., in press, 1996.

Seeber, L. and J.G. Armbruster, The San Andreas fault system through the Transverse Ranges as illuminated by earthquakes, *J. Geophys. Res.,* **v. 100,** p.8285–8310, 1995.

Seeber, L. and C.Sorlien, Listric thrusts in the western Transverse Ranges, California, submitted, 1997.

Shaw, J.H. and J. Suppe, Active faulting and growth folding in the eastern Santa Barbara Channel, California, *Geol. Soc. Am. Bull.,* **v. 106,** p. 607–626, 1994.

Sorlien, C.C, Structure and Neogene evolution of offshore Santa Maria basin and western Santa Barbara Channel, California, Ph.D. Dissertation, UC at Santa Barbara, 219 pp plus plates (1994).

Sorlien, C.C., J-P Gratier, B.P. Luyendyk, J.S. Hornafius, and T.E. Hopps, 1995, Finite-displacement field across the Oak Ridge fault: Restoration of a folded and faulted layer near onshore and offshore Ventura Basin, California, *preprint*, 1995.

Suppe, J., *Principals of Structural Geology,* Prentice-Hall, Englewood Cliffs, NJ, 537 p., 1985.

Suppe, J., R.E. Bischke and J.H. Shaw, Evaluation of the use of compressive growth structure in earthquake hazard assessment, *U.S. Geol. Surv. Open-file Report 91-352,* 192–195, 1991.

Suppe, J. and D.A. Medwedeff, Geometry and kinematics of fault-propagation folding, *Eclogae Geol. Helv.,* **v.83/3,** p. 409–454 (1990).

Sylvester, A., Aseismic growth of Ventura Avenue anticline (1978 to 1991); Evidence of anelastic strain release in Ventura basin, southern California, *Eos (Trans. AGU),* **v.76,** p.F141, 1995.

Thibaut, M., J.P. Gratier, M. Léger, and J.M. Morvan (1996). An inverse method for determining three-dimensional fault geometry with thread criterion: application to strike-slip and thrust faults, *J. Structural Geol.,* **v.18,** p. 1127–1138.

Yeats, R. S., Late Quaternary slip rate on the Oak Ridge Fault, Transverse Ranges, California: Implications for seismic risk: Journal of Geophysical Research, **v. 93,** p. 12,137-12,149, 1988.

Yeats, R.S., 1983, Larege-scale Quaternary detachments in Ventura basin, southern California, *J. Geophys. Res.,* **88,** p. 561–583.

Yeats, R.S., G.J. Huftile, and F.B. Grisby, 1988, Oak Ridge fault, Ventura fold belt, and the Sisar decollment, Ventura basin, California, *Geology,* **v. 16,** p. 1113–1116.

Yeats, R.S. (1993). Converging more slowly, *Nature,* **v. 366,** p. 299-301.

Yeats, R.S., G.J. Huftile, and L.T. Sitt, Late Cenozoic tectonics of the east Ventura basin, California, Am. Asoc. Petrol. Geol. Bull., v. 78, p.1040-1074, 1994.

Yeats, R.S., Thin-skinned vs thick-skinned interpretation of seismogenic reverse faults, *SCEC Workshop on Thrust Ramps and Detachment Faults in the Western Transverse Ranges,* p. 29–30, UC Santa Barbara, January, 1995.

Yeats, R.S. and G.J. Huftile (1995). Oak Ridge fault system and the 1994 Northridge, California, earthquake, *Nature,* **v.373,** p. 418–420.

Yerkes, R.F. and W.H.K. Lee (1979). Maps showing faults and fault activity, epicenters, focal depths, and focal mechanisms for the 1970-1975 earthquakes, western Tranverse Ranges, California, *U.S. Geol. Surv. Misc. Field Studies Map MF-1032.*

Ziony, J.I. and L.M. Jones, Map showing late Quaternary faults and 1978–84 seismicity of the Los Angeles region, California, U.S. Geol. Surv. Map MF–1964, scale 1:250,000, 1989.
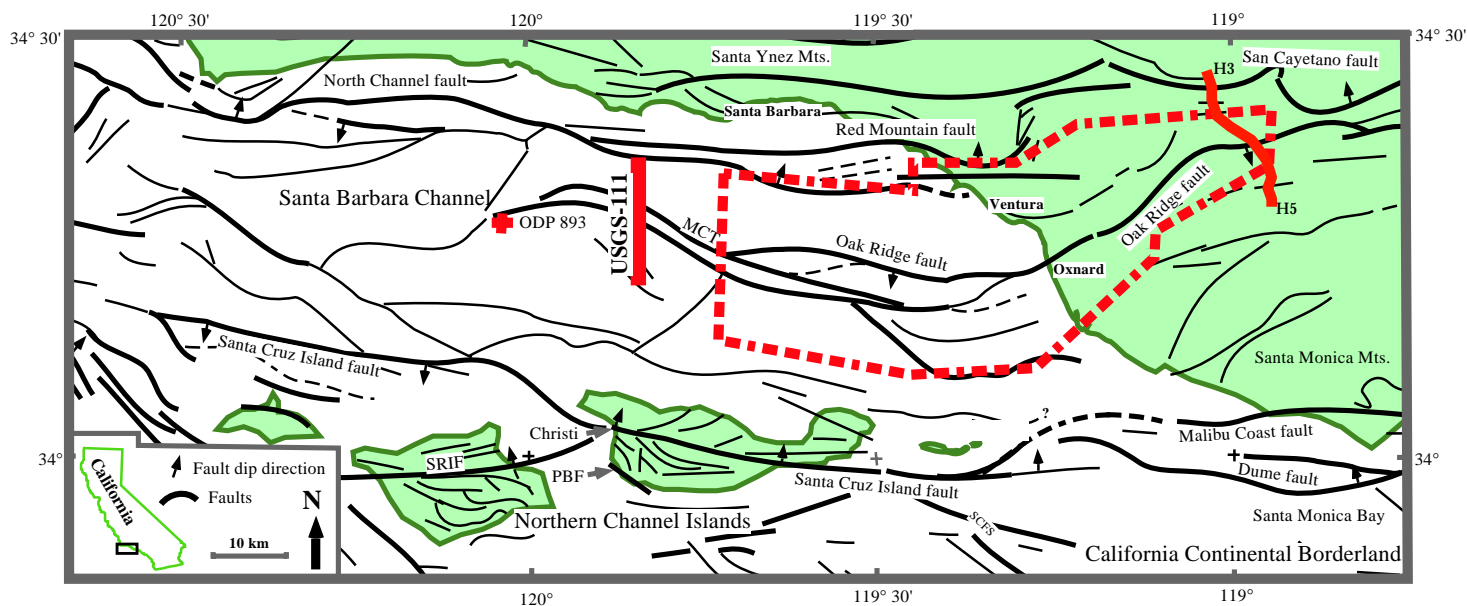
Figure 1 (top). Map of Santa Barbara Channel and Ventura Basin showing current area of study (dashed region), and location of example Ventura Basin cross section (red line, far right) shown below. In addition to onshore industry data, we also have extensive well data, stratigraphic control, and grids of multichannel seismic data in the offshore Santa Barbara Channel.

Ventura Basin Study Group Cross Section H5-H3 showing the thrust overlap of the mapped horizons across the Oak Ridge fault.
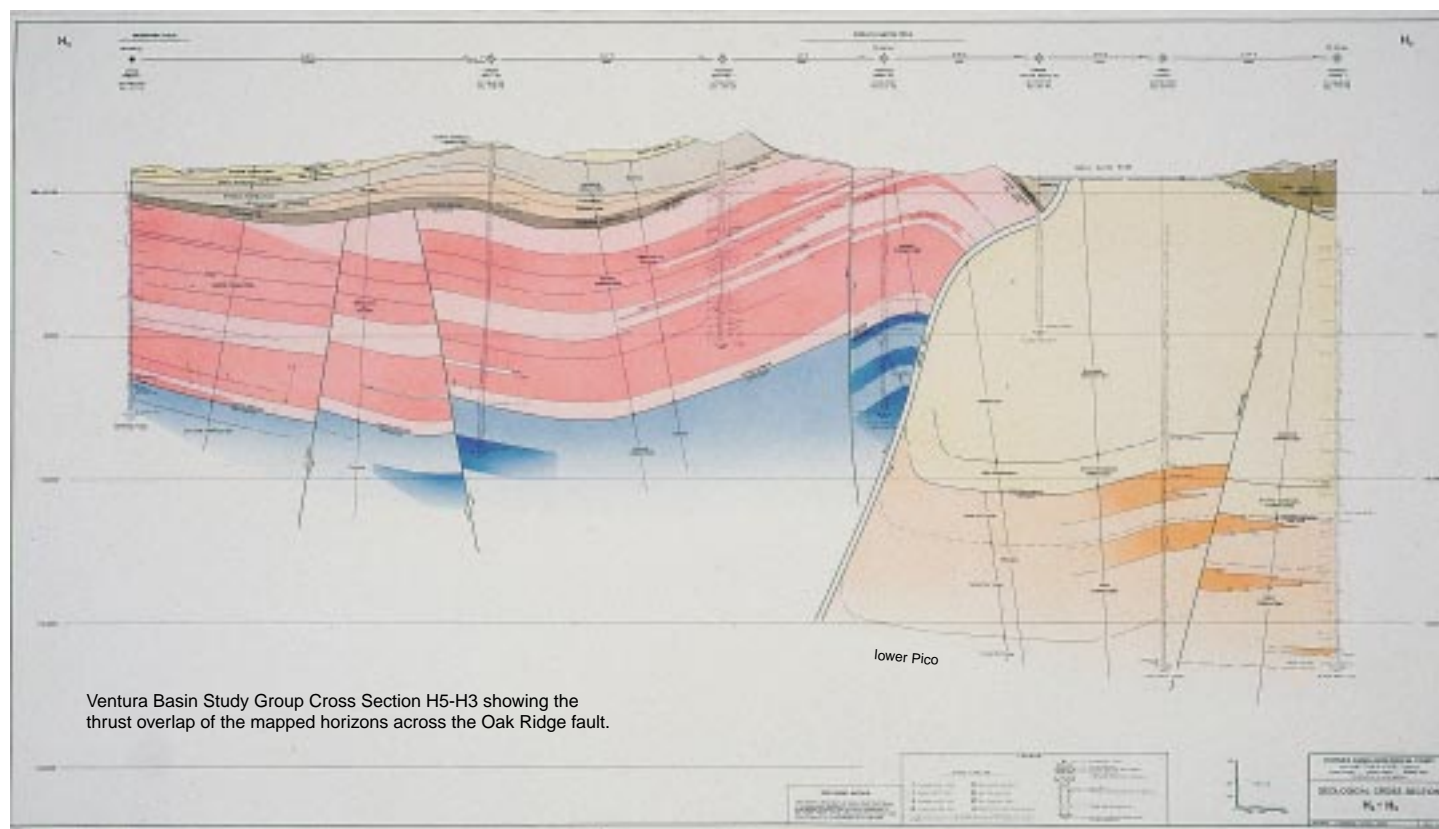
lower Pico

Figure 1 (bottom). Example of a Ventura Basin Study Group cross section data panel based on extensive industry drillhole data. Each data panel ties in 4 directions to define the sides of a 3D volume or cell, thus describing the subsurface structure in 3-dimensions. This panel shows Miocene age (red) and older rocks thrust up and over younger Plio-Pleistocene age sediments (yellow) along the Oak Ridge fault.

Figure 2 (top). 2D balanced cross section model across the Ventura basin [*Namson and Davis,* 1992]. Note the simple ramp-flat geometry of thrust faults, the shallow depth of the detachment (7 km), and the absence of a south-dipping Santa Ynez fault. Compare with Figure 8. Because these 2D models involve the motion of material up rigid thrust ramps, the model fails to account for the deep (10-12 km) subsiding central Ventura basin, or the footwall deformation this subsidence requires. Much of this subsidence occurred during convergence (since 4 Ma).

Figure 2 (bottom). Alternate 2D balanced cross section model [*Huftile and Yeats,* 1996]. This model explains much of the observed subsurface structure, especially the Red Mountain fault, but does not predict the south-dipping Santa Ynez fault, the curviplanar fault defined by the 1996 Ojai sequence (Figure 8), or—as in the 2D model above—account for the substantial subsidence in the basin since shortening began.
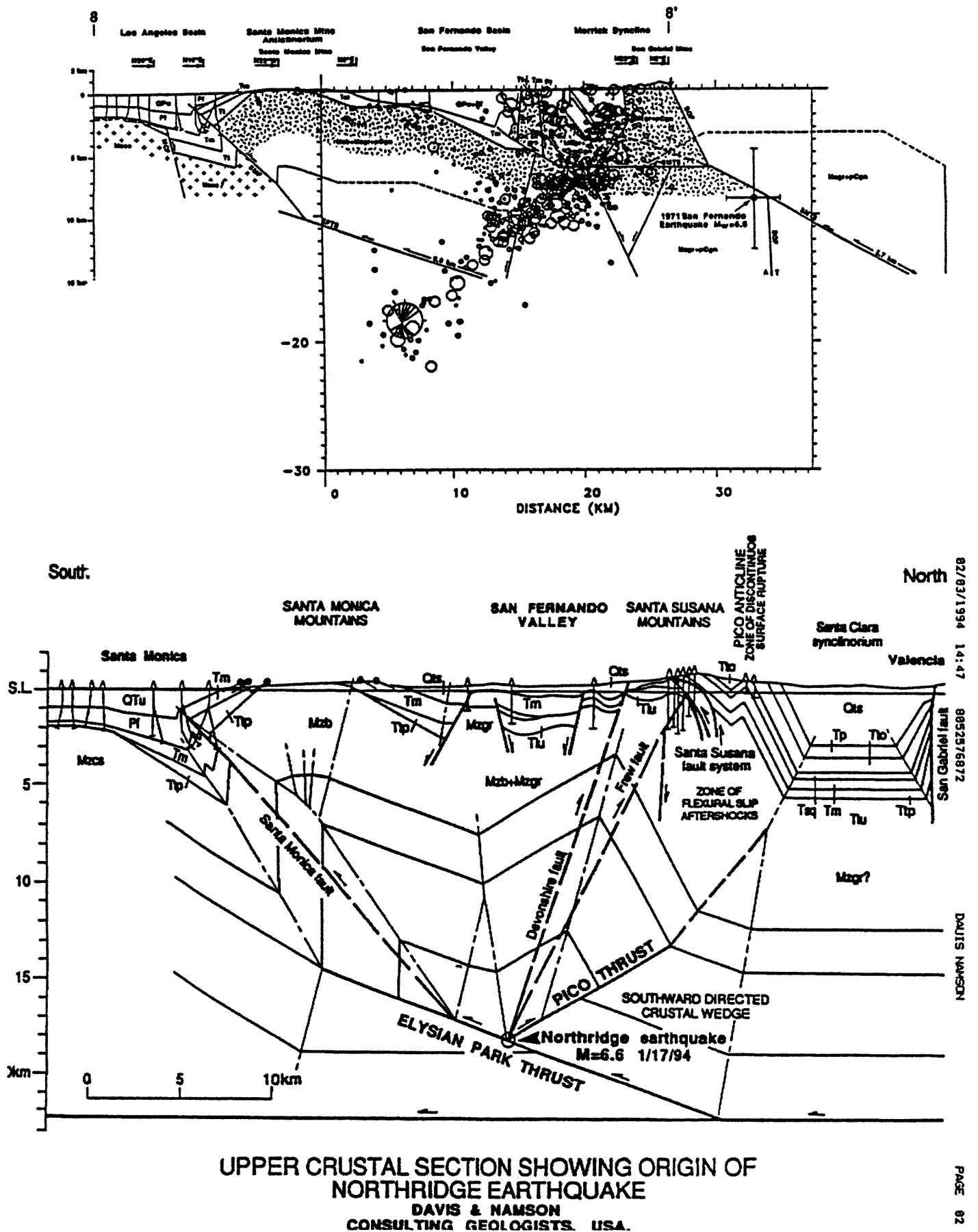
Figure 3. 2D balanced cross section models through the San Fernando Valley developed before (top) and after (bottom) the 1994 M6.7 Northridge earthquake using the exact same near-surface data. Note the lack of a south-dipping fault responsible for the earthquake in the original model and the change in the deep fault/fold geometry.
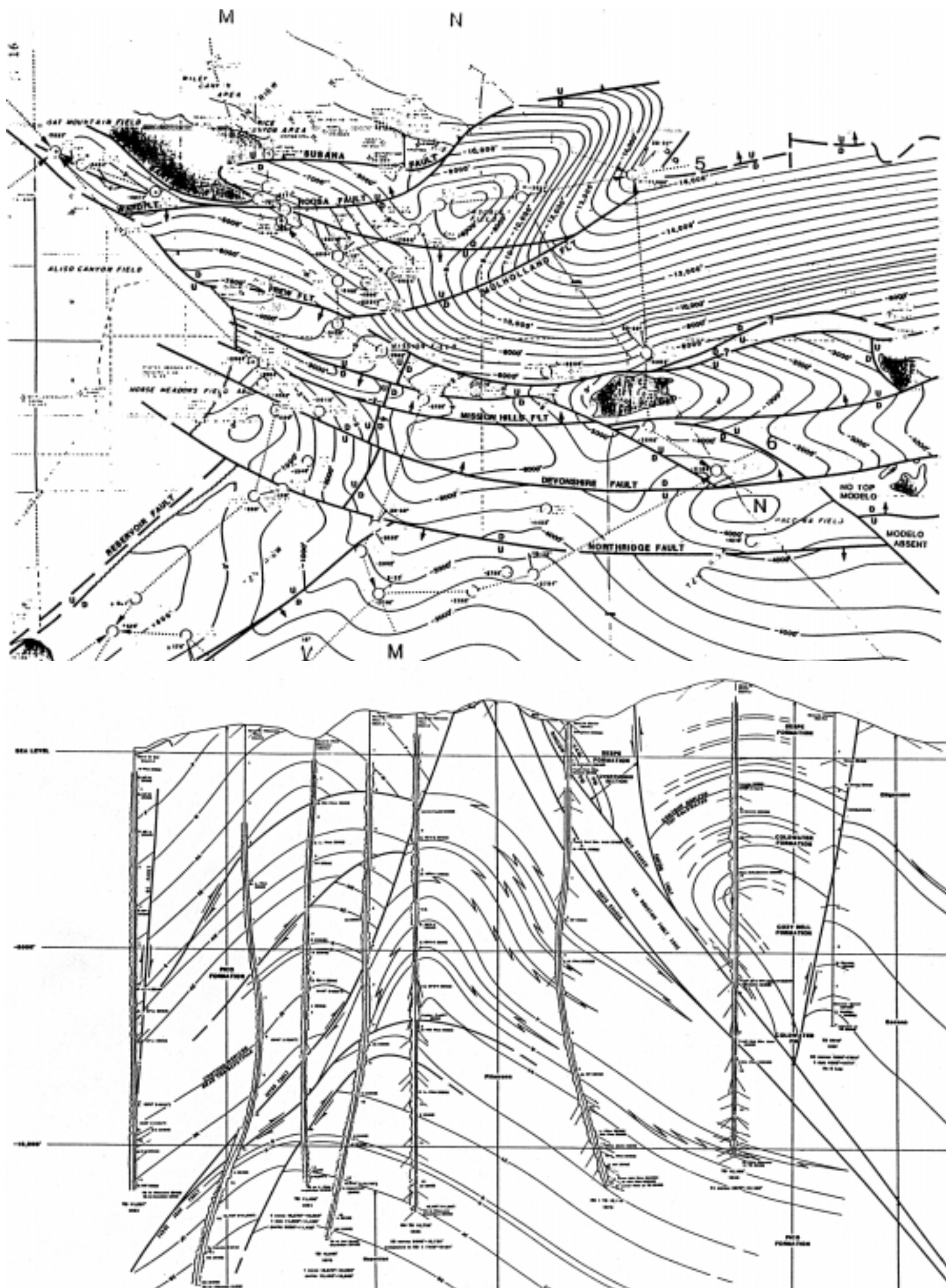
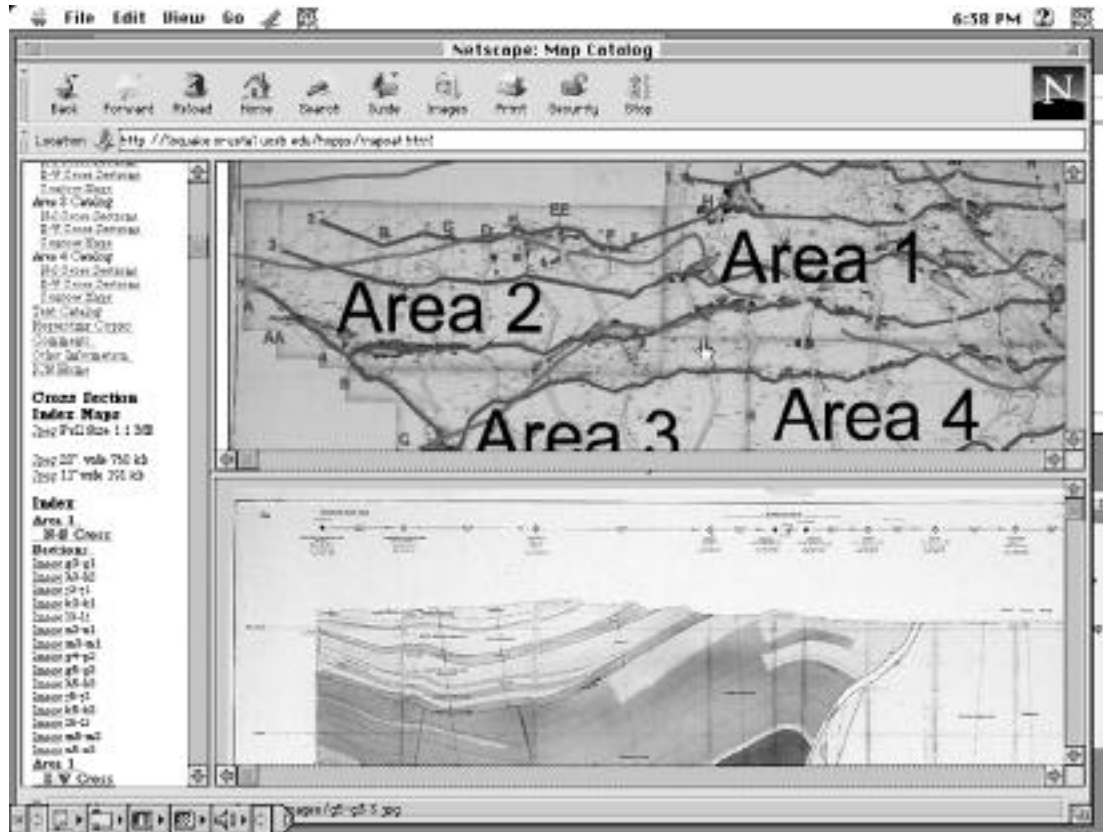Figure 4. Examples of parts of VBSG structure contour maps (top) and cross section data panels (bottom).

Figure 5 (top). Screen image of the ICS Ventura Basin Study Group website. The VBSG website includes a clickable cross section index map (top right), a simple text catalog (left), and a thumbnail image catalog (not shown), that allows users to access individual images of VBSG structure maps and cross sections (e.g., lower right).
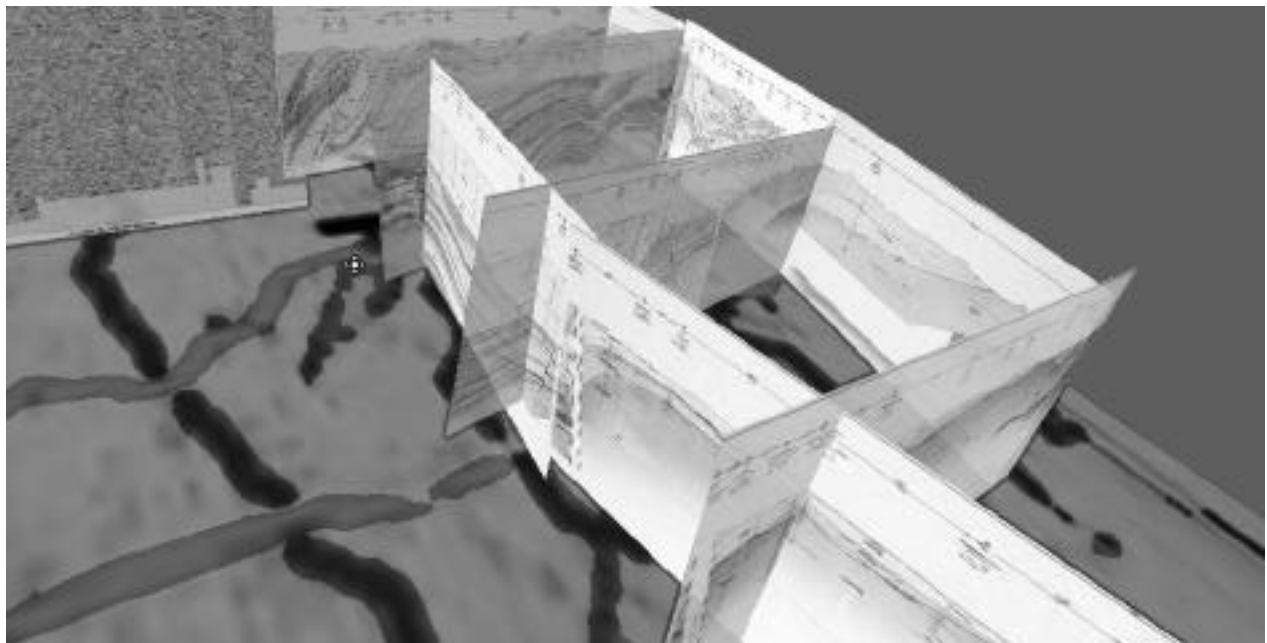

Figure 5 (bottom). Prototype 3D VRML image of VBSG cross sections viewable from our ICS VBSG website (requires Navigator 4.0, Netscape plug-in, or SGI computer to access).
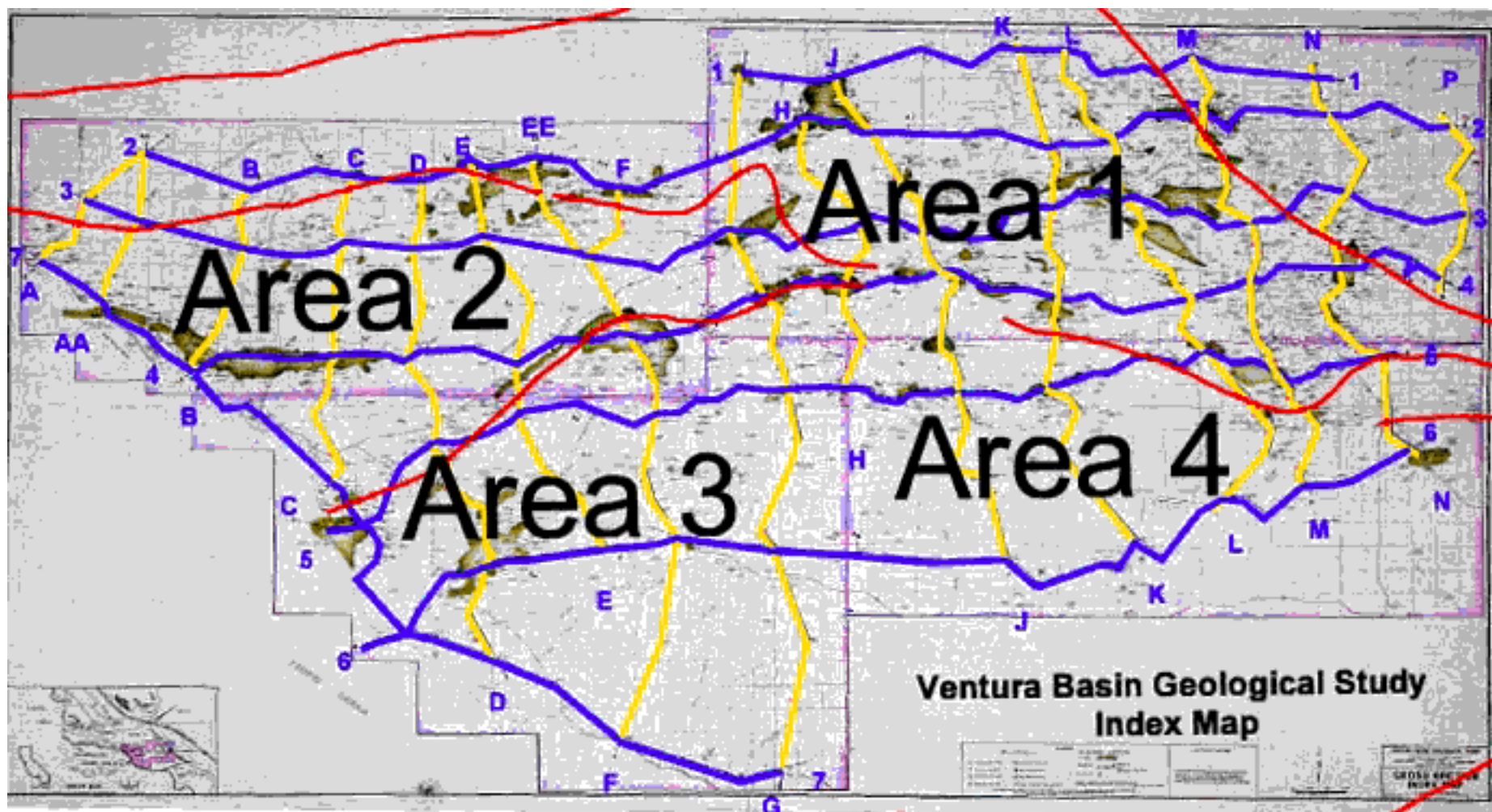
Figure 6. Enlarged VBSG cross section index map. The ICS VBSG website includes an interactive, clickable version of this map that allows users to select individual VBSG cross section data panels for viewing. The website is located at: http://www.crustal.ucsb.edu/.
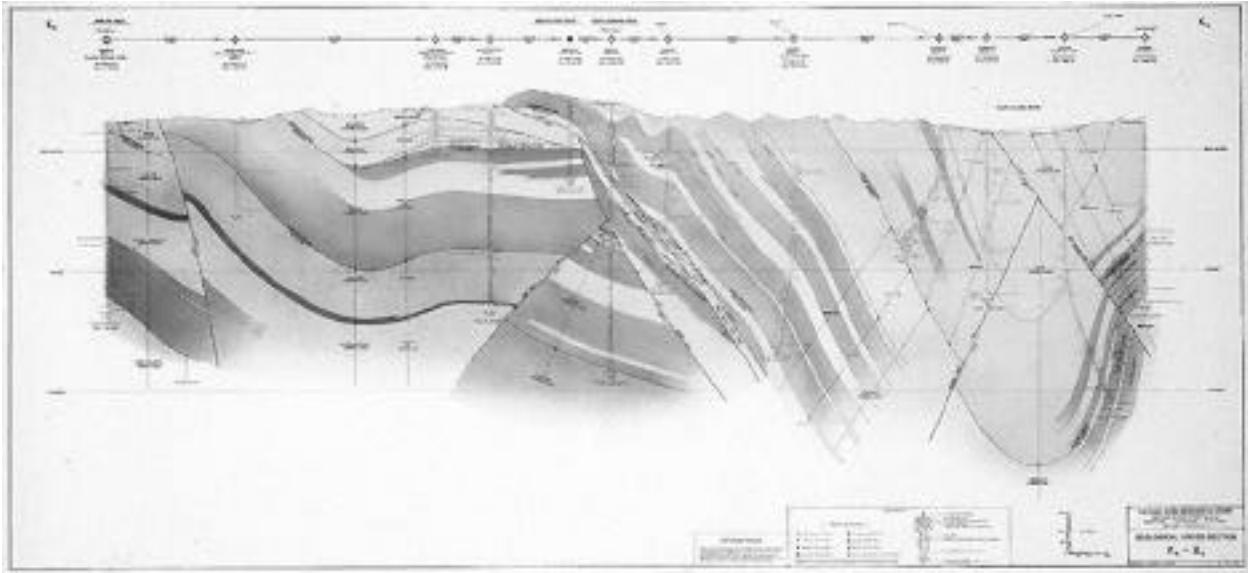
Figure 7 (top). North-South VBSG cross section data panel across the Santa Susana fault showing the presence of a significant south-dipping blind fault in the footwall block. This blind structure is part of the same fault system responsible for the 1994 Northridge earthquake.
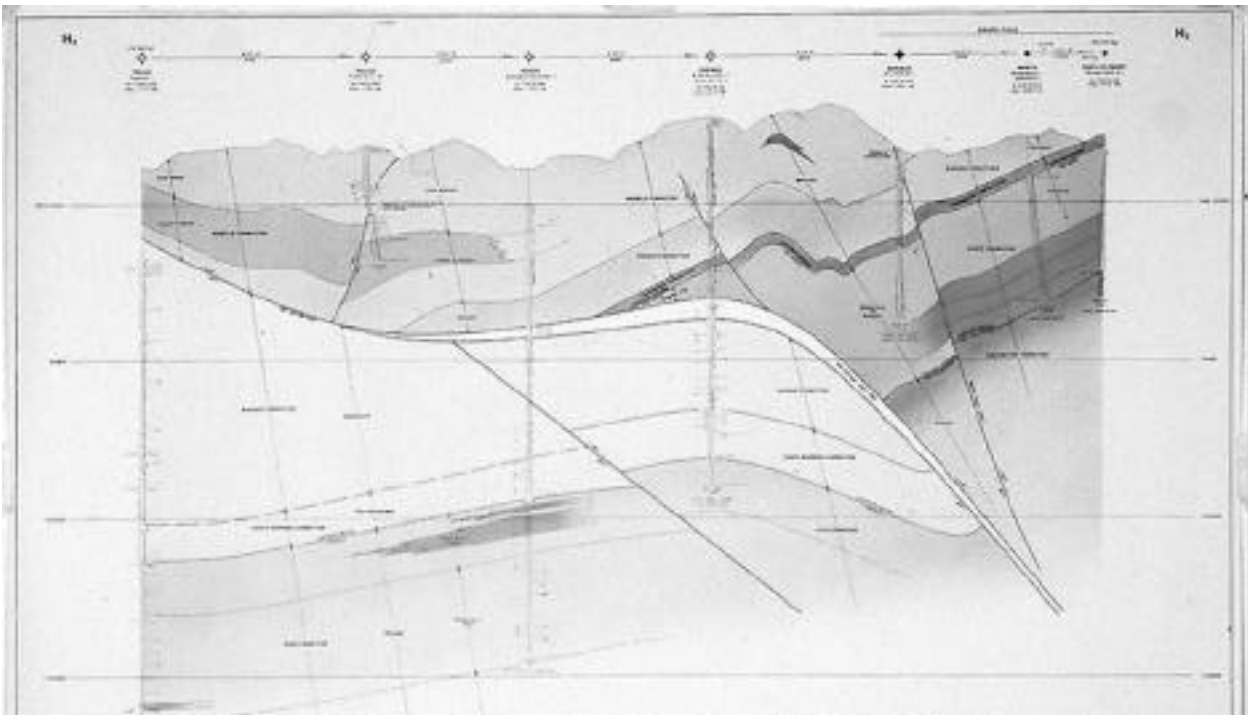

Figure 7 (bottom). North-South VBSG cross section data panel across the Santa Susana fault showing significant non-planar fault geometry, inconsistent with 2D planar fault models (Fig.2).
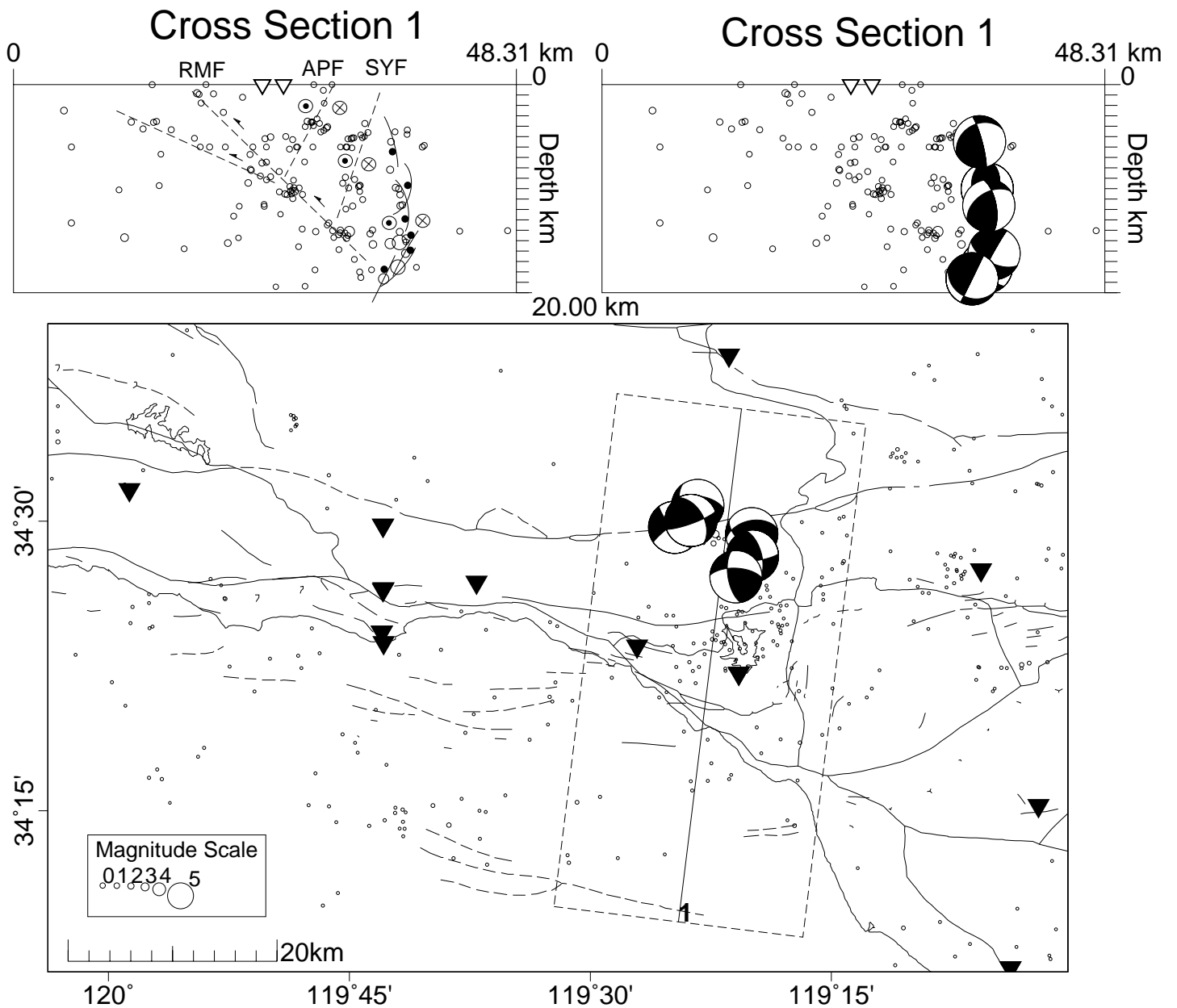
Figure 8. (top) Vertical cross section views of recent seismicity (1994–1996) and the 1996 M4.6 Ojai sequence showing interpretation of active subsurface faults (left) and focal mechanisms of the Ojai events (right). (bottom) Map view of earthquakes and focal mechanisms. Note alignment of hypocenters along the north-dipping Red Mountain fault (RMF), a south-dipping Arroyo Parida (APF) and Santa Ynez faults (SYF), and a curviplanar fault whose surface projection would also correspond with the SYF.

Figure 9 (top). 3D perspective view looking west of a specific
stratigraphic (time) horizon in the onshore Ventura basin.
Modified from Yeats [1981] using the VBSG dataset [Kamerling et al., 1998].
This horizon is ~1 Ma, and reflects the cumulative effects of folding and faulting since that time.

Figure 9 (bottom). Finite strain field
derived from the digitial 3D surface
of the ~1 Ma horizon (above). Each
block was separately unfolded using
the techniques of [Gratier et al., 1991]
to produce a measure of the internal
%strain due to folding. Blocks were
then fitted together to yield an estimate
 of cumulative fault offset. In this
version, the Oak Ridge fault exhibits
about 1.7 km of left slip, but variable
amounts of reverse slip along strike.